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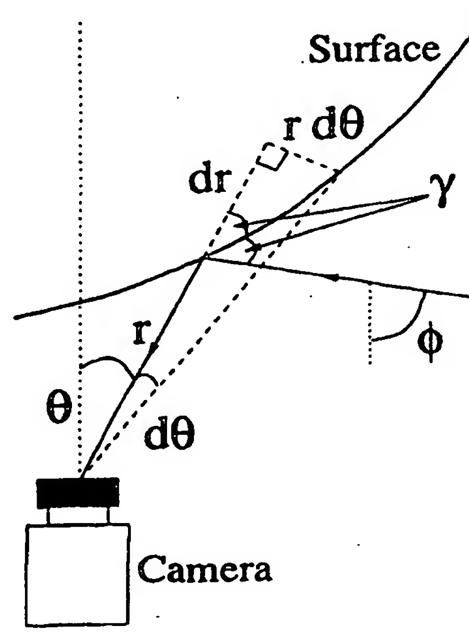
(57) Abstract

A panoramic imaging system includes an imaging device having an image plane and a first field of view, a first reflective surface having at least one circularly symmetric portion convex in a radial direction disposed in the first field of view to provide an expanded panoramic second field of view. The profile of the or each convex portion provides a varying gain between the fields of view in the radial direction to limit variation in the solid angle of view across the image plane of the imaging device.



RESOLUTION INVARIANT PANORAMIC IMAGING

FIELD OF THE INVENTION

This invention relates to generating wide angle images of spaces, generally referred to as panoramic imaging.

BACKGROUND ART

Panoramic imaging is becoming an important tool in the area of mobile robotics and machine vision. There are many documented methods for recording a panoramic view of a scene. One simple method involves having a series of cameras mounted on a ring to give views around the entire 360° of horizon. This involves, say, four cameras if they each have a field of view of 90° and some integration of images. There are also a number of single camera methods for panoramic imaging, including rotating a camera about its vertical axis and taking pictures continuously to obtain a full panoramic view. Another approach uses wide angle lenses to achieve a large field of view, but these lenses are heavy, expensive and distort the image.

An attractive approach to panoramic imaging is to mount a single fixed camera under a curved reflective surface covering a hemisphere such as with a conical, spherical, hyperboloidal, or other profile. The optical axis of the camera is aligned with the central axis of the mirror. A known family of constant gain reflective surfaces have the advantage that they can produce large fields of view such as for a hemispherical or hyperboloidal mirror yet preserve a linear relationship between changes in angles of incidence and reflection of light rays viewed by the camera. This linear relationship simplifies image processing and ensures constant elevational resolution of the image. The shape of the surface is determined by the gain of the linear relationship. For a unity gain, the surface is a cone; for higher gains, the surface is specified by a family of polynomial functions. For ease of explanation in this specification the panoramic plane will be considered as being horizontal and the field of view as vertical as would be the case for a robot moving in a horizontal plane. It will be apparent that in the general case orientation of the planes is arbitrary.

All the mirror shapes mentioned above share a common draw back. That is that the CCD cameras used for imaging invariably have uniform Cartesian arrays of pixels to capture the polar image of the scene, and so the pixel density per solid angle increases with the radius of the polar image. The unwarping process transforms the image from polar to Cartesian coordinates so that the angular coordinate in the original polar image maps to the x-coordinate in the unwarped image while the radial coordinate maps to the y-coordinate. Thus the pixel density in the unwarped image varies from low for small x values which correspond to the centre of the original image to high for large x values which correspond to the outer rim of the polar image. This is illustrated in Figure 1 which shows the unwarping of an image captured with a hyperboloidal mirror. The variation in image quality is clearly evident in the unwarped version.

One way to circumvent this problem is to use a specially designed CCD camera with a polar array of pixels with a pixel density which decreases with radius. There are alignment problems with such an approach.

DISCLOSURE OF THE INVENTION

In a first aspect this invention provides a panoramic imaging system including an imaging device having an image plane and a first field of view, a first reflective surface having at least one circularly symmetric portion convex in a radial direction disposed in said first field of view to provide an expanded panoramic second field of view, the profile of the or each convex portion providing a varying gain between the fields of view in the radial direction to limit variation in the solid angle of view across the image plane of the imaging device.

Preferably, the profile of the convex portion provides a substantially uniform solid angle of view across the image plane. That is, the shape ensures that the resolution in the image is invariant to changes in elevation. Thus, where the imaging system involves a device with an array of uniformly spaced pixels in the image plane, the shape of the reflective surfaces results in solid angle pixel density invariance.

The profile of the reflective surface in polar coordinates is preferably determined by solving the equation

$$\frac{dr}{d\theta} = r \cot\left[-\tfrac{1}{2}\int(1 + \alpha(\theta))\, d\theta\right]$$

where r is the radial distance from the reflective surface to the imaging device

θ is the angle from the optical axis of the imaging device

$\alpha(\theta)$ is the mirror gain given by

$$\alpha(\theta) = B_\alpha [\tan(\theta) + \tan^3(\theta)]$$

$$B_\alpha = \frac{2(\overline{\phi} - \underline{\phi})}{\tan^2(\overline{\theta}) - \tan^2(\underline{\theta})}$$

$\overline{\phi}$ and $\underline{\phi}$ are the maximum and minimum elevations viewed $\overline{\theta}$ and $\underline{\theta}$ are the maximum and minimum radial angles imaged.

In one approach r can be plotted against θ at selected intervals to describe the profile by solving the above equation for selected values of θ. For example determining values of r for incremental values of θ of about 1/5° has been found to produce a sufficiently accurate profile for practical application.

There are a number of methods for panoramic range finding. One method uses a cone mirror above a camera. The camera mirror assembly is either displaced during image collection, or two camera mirror assemblies are used to obtain the two views necessary for range finding. Although this method provides range information in the horizontal plane at video rates, its drawbacks are that no range information is available in the vertical (elevation) direction, objects must be more than a minimum distance from the camera and there may be a blind spot

due to the second camera system.

A discontinuous, axially symmetric mirror, which is in essence a coaxial mirror pair, mounted above a camera to obtain two views of a panoramic scene for stereo disparity range finding is known. There are however no proposals concerning specific mirror shapes to achieve specific desirable properties. Additionally, known constant gain mirror profiles have been generalised to derive a family of such coaxial mirror pair profiles for panoramic stereo imaging and processing based on disparities in the vertical plane.

In another aspect this invention provides for range finding using a panoramic imaging system containing two resolution invariant mirrors. Preferably the mirror or reflector surface has at least two of said convex portions arranged to respectively provide at least partially overlapping panoramic second fields of view for range determination. The second fields of view are preferably substantially co-incident. In the preferred form of the invention the two convex portions form a continuous mirror or reflective surface.

In a further aspect this invention provides a design for a back to back stereo mirror system with the desirable property of equal pixel sharing between two cameras and thus the two stereo images. The stereo cone in this case is preferably symmetric in the directions orthogonal to the camera axis which is a desirable property for some applications. In this aspect of the invention the imaging system preferably includes two first reflective surfaces each having an associated image plane with corresponding first fields of view, and at least one convex portion of each first reflective surface providing respective panoramic second fields of view, said first reflective surface being arranged back to back such that said reflective second fields of view at least partially overlap.

A second reflective surface can, in some applications be interposed between the image plane and the second reflective surface. This allows positioning of the imaging device for example behind the first reflective surface. In some variations an apperture can be provided in the first reflective surface to provide the first field of view from the imaging device.

In another aspect this invention provides a reflective surface for use in a panoramic imaging system including an imaging device having an imaging plane and a first field of view, said reflective surface having at least one circularly symmetric portion convex in a radial direction with a profile providing varying gain in the radial direction between an expanded panoramic second field of view provided by the reflective surface and the first field of view to limit variation in the solid angle of view across the image plane of the imaging device.

In yet a further aspect this invention provides mirrors having minimal intrusive designs, which intrude to a minimal extent into the viewing "hemisphere". These are also termed forward facing designs. They involve an additional planar mirror and camera relocation within the primary reflective surface. The attraction of this arrangement is that the first reflective mirror surface profile is the same design as in a more conventional arrangement.

The invention will be further described, by way of example only with reference to the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 illustrates an unwarping process for a prior art panoramic imaging system;

Figure 2 schematically shows the relationship between camera image and horizontal view direction in a panoramic imaging system;

Figure 3 illustrates geometric relationships between a reflecting surface and a camera used to derive mirror profiles according to this invention;

Figures 4A and 4B, are graphs showing a comparison of a constant gain mirror with a variable gain mirror used in the imaging system according to this invention;

Figures 5A and 5B, shows ray traced scenes respectively reflected in constant and variable gain mirrors;

Figures 6A and 6B, graphically illustrates a comparison of panoramic imaging systems respectively utilising double constant and variable gain mirror configurations;

Figures 7A and 7B, shows raced traced images of scenes respectively corresponding to panoramic imaging systems utilising double constant and variable gain mirror configurations;

Figure 8 schematically illustrates relationships between camera and reflective surfaces used in range calculation utilising a resolution invariant double mirror according to this invention;

Figure 9 schematically illustrates a back to back mirror configuration according to this invention;

Figure 10 schematically illustrates a double back to back mirror configuration according to this invention;

Figure 11 schematically illustrates a forward looking panoramic imaging system according to this invention; and

Figure 12 shows a system utilising a combination of the arrangements in Figures 10 and 11.

BEST MODE FOR CARRYING OUT THE INVENTION

The various aspects of this invention will, for clarity, be described under separate subheadings.

1 Resolution Invariant Mirror Families

This section describes a family of mirror designs that achieve the objective of resolution invariance, or equivalently solid angle pixel density invariance.

1.1 Constant Image Pixel Density - The Variable Gain (α) Mirror

In accordance with one aspect of this invention resolution invariance is achieved by adjusting the mirror profile to image relatively less of the scene in the centre of the image and relatively more at the perimeter. That is, a mirror profile is selected to maintain a constant relationship between the pixel density and the angle of elevation in the scene or more precisely, the solid angle. The mirror gain α, is the relationship between the change in elevation of rays incident on the mirror and the change in the angle of rays reflected into the camera as follows

$$\alpha = \frac{\delta\phi}{\delta\theta} \tag{1}$$

where $\delta\phi$ is the change in vertical elevation and $\delta\theta$ is the change in angle of reflected rays received by the camera. With resolution invariance α becomes a function of image angle θ which is related to the radial coordinate in the image, ρ, as shown in Figure 2.

Figure 3 schematically shows an imaging system including an imaging device in the form of a camera having an image plane and a first field of view. A reflective surface or mirror is ... in the first field of view to provide an expanded panoramic second field of view. The surface is circularly symmetric and convex in a radial direction.

Consider a mirror profile (r, θ) in polar coordinates where r is the radial distance to the camera and θ is the angle from the optical axis of the camera to the point on the mirror surface as shown in Fig. 3. The angle of incidence of a light ray relative to the mirror is γ and the angle of an incoming light ray with respect to the vertical is ϕ. Then

$$\gamma = \tan^{-1}\left(\frac{rd\theta}{dr}\right) \qquad (2)$$

subject to the geometric constraint (from the law of reflection)

$$2\gamma + \theta + \phi = \pi \qquad (3)$$

Differentiating (2) and (3) with respect to θ

$$\frac{d\gamma}{d\theta} = \frac{d}{d\theta}\left[\tan^{-1}\left(\frac{rd\theta}{dr}\right)\right] \qquad \textit{From (2)}$$

$$\frac{d\gamma}{d\theta} = -\frac{1}{2}\left(1 + \frac{d\phi}{d\theta}\right) \qquad \textit{From (3)}$$

so, substituting α from (1) gives

$$\frac{d}{d\theta}\left[\tan^{-1}\left(\frac{rd\theta}{dr}\right)\right] = -\frac{1}{2}(1+\alpha) \qquad (4)$$

Now, for a variable gain mirror, α is a function of image angle θ (related to the radial coordinate in the image, ρ) so (4) becomes

$$\frac{d}{d\theta}\left[\tan^{-1}\left(\frac{rd\theta}{dr}\right)\right] = -\tfrac{1}{2}(1+\alpha(\theta)) \qquad (5)$$

or, rearranging

$$\frac{dr}{d\theta} = r \cot\left[-\tfrac{1}{2}\int(1+\alpha(\theta))\,d\theta\right] \qquad \textbf{(6)}$$

The equation for the mirror gain, $\alpha(\theta)$ to achieve pixel density invariance can be found using the following theory.

1.1.1 Pixel Density Invariance Profiles

There are $p(\rho)$ pixels in an area of radius ρ in the image. More formally, there are

$$p(\rho) = \pi\kappa\rho^2$$

pixels in an area of radius ρ, where κ is the number of pixels per unit area, a constant. Differentiating by ρ gives

$$\frac{\partial p(\rho)}{\partial\rho} = 2\pi\kappa\rho \qquad \textbf{(7)}$$

Now, the radius in the image, ρ is related to the radial angle of a ray reflected from the mirror, θ by the focal length of the camera, f (a constant)

$$\rho = f\tan(\theta) \qquad \textbf{(8)}$$

so differentiating $p(\rho)$ by θ and substituting (7) and (8) gives

$$\begin{aligned} \frac{\partial p(\rho)}{\partial \theta} &= \frac{\partial p(\rho)}{\partial \rho}\frac{\partial \rho}{\partial \theta} \\ &= 2\pi\kappa\rho f \frac{\partial \tan(\theta)}{\partial \theta} \\ &= 2\pi\kappa f^2 \tan(\theta)(1 + \tan^2(\theta)) \end{aligned} \tag{9}$$

Now, it is required that the image pixel density be invariant to angle of elevation in the scene which leads to more of the scene being imaged towards the perimeter, so

$$p(\rho) = \beta\phi + C(\phi) \tag{10}$$

where β and $C(\phi)$ are constants. Differentiating both sides of (10) by ϕ and substituting (1) and (9) gives

$$\begin{aligned} \beta\frac{\partial \phi}{\partial \phi} &= \frac{\partial p(\rho)}{\partial \phi} \\ \beta &= \frac{\partial p(\rho)}{\partial \theta} \bullet \frac{\partial \theta}{\partial \phi} \\ &= \frac{2\pi\kappa f^2 \tan(\theta)(1 + \tan^2(\theta))}{\alpha(\theta)} \end{aligned} \tag{11}$$

Rearranging (11) gives

$$\begin{aligned} \alpha(\theta) &= \left(\frac{2\pi f^2\kappa}{\beta}\right) \tan(\theta)[1 + \tan^2(\theta)] \\ &= B_\alpha [\tan(\theta) + \tan^3(\theta)] \end{aligned} \tag{12}$$

where B_α is a constant. Integrating this expression for $\alpha(\theta)$ by θ gives an expression for ϕ (see (1)), the elevation of an object imaged at angle θ. That is

$$\phi = \frac{B_\alpha}{2}\tan^2(\theta) + \phi(\theta = 0) \tag{13}$$

where ϕ $(\theta = 0)$ is a constant of integration.

The constants B_α and ϕ $(\theta = 0)$ can be determined from the maximum and minimum values of θ and ϕ which are known for a desired mirror configuration, using (13).

$$\begin{aligned} B_\alpha &= \frac{2(\overline{\phi} - \underline{\phi})}{\tan^2(\overline{\theta}) - \tan^2(\underline{\theta})} \\ \phi(\theta = 0) &= \underline{\phi} - \frac{B_\alpha}{2}\tan^2(\underline{\theta}) \end{aligned} \tag{14}$$

It appears not possible to find an analytical solution to (6) if α is a function of θ, so there is no explicit equation for the mirror shape. Instead, a differential equation solver is needed to find solutions to (6) over the range of θ (the mirror surface).

Figures 4A and 4B show for comparison a constant gain mirror and a variable gain mirror with the same camera field of view and range of elevations imaged. The rays shown are constantly spaced in θ, with about 2° between each ray. It is clear from Fig. 4A that in the constant gain case these rays are constantly spaced in ϕ, with about 8.5° between each ray, and from Fig. 4, that the spacing between the rays in the variable gain case increases with increasing ϕ. So, in the variable gain case, a greater proportion of the scene is imaged towards the outer edge of the polar image. This is also shown in Figures 5A and 5B, ray traced images reflected in a constant gain and variable gain mirror with the same range of elevations visible.

1.2 Panoramic Stereo Using a Variable Gain Mirror

A mirror with two convex portions or a double mirror is required. The radial profile of a double mirror is shown in Figure 8. The mirror arrangement for panoramic stereo with variable gain mirrors will necessarily be different than for constant gain mirrors due to the variation of the mirror gain, α. The gain must vary in a constant fashion over the entire double mirror so that the constant pixel density

theorem will hold over the entire image. If the minimum and maximum elevations viewed ($\underline{\phi}$ and $\overline{\phi}$) are to be equal for both mirrors in the double mirror system, the range of reflected angles ($\overline{\theta} - \underline{\theta}$) cannot be equal for the two mirrors. The minimum and maximum angles of reflected rays captured by the camera over the entire mirror surface are known from camera geometry. Therefore the minimum ray reflected from the lower mirror ($\underline{\theta_1}$) and the maximum ray reflected from the upper mirror ($\overline{\theta_2}$) are known. So, since (12) holds over the entire mirror, B_α is constant, and from (14)

$$\begin{aligned} \frac{2(\overline{\phi} - \underline{\phi})}{(\tan^2(\overline{\theta_1}) - \tan^2(\underline{\theta_1}))} &= \frac{2(\overline{\phi} - \underline{\phi})}{\tan^2(\overline{\theta_2}) - \tan^2(\underline{\theta_2})} \\ \tan^2(\overline{\theta_1}) - \tan^2(\underline{\theta_1}) &= \tan^2(\overline{\theta_2}) - \tan^2(\underline{\theta_2}) \\ \tan^2(\overline{\theta_1}) + \tan^2(\underline{\theta_2}) &= \tan^2(\overline{\theta_2}) + \tan^2(\underline{\theta_1}) \end{aligned} \tag{15}$$

It is desirable to minimise the gap in the radial direction between the images from the two mirrors so as to maximise usage of the camera field of view. For minimum gap $\overline{\theta_1} = \underline{\theta_2}$, so

$$\begin{aligned} 2\tan^2(\overline{\theta_1}) &= \tan^2(\overline{\theta_2}) + \tan^2(\underline{\theta_1}) \\ \overline{\theta_1} &= \tan^{-1}\left[\left(\frac{\tan^2(\overline{\theta_2}) + \tan^2(\underline{\theta_1})}{2}\right)^{1/2}\right] \end{aligned} \tag{16}$$

Figures 6A, 6B and 7A, 7B show graphical and ray traced comparisons of constant and variable gain double mirror systems viewing the same scene.

2.4 Calculation of Range for a Variable Gain Panoramic Stereo System

The information available for range calculation are the image angles for a single object reflected in both mirrors, θ_1 and θ_2 as shown in Figure 8. The two mirrors θ_1 and θ_2 form a reflective surface. The differential equations (6) for the surfaces are known. In the calculations that follow only the lower mirror is examined as the results are identical for the upper mirror.

In order to find the position of object P, the equations of the incident beams from *P* to each mirror reflection point (r_1, θ_1) and (r_2, θ_2) must be found. These equations can then be solved simultaneously to give the position of object *P*, (x_P, y_P).

$$\begin{bmatrix} y_P \\ x_P \end{bmatrix} = \begin{bmatrix} 1 & -m_{I1} \\ 1 & -m_{I2} \end{bmatrix}^{-1} \begin{bmatrix} C_{I1} \\ C_{I2} \end{bmatrix}$$

$$= \begin{bmatrix} -\dfrac{m_{I2}}{m_{I2}-m_{I1}} & \dfrac{m_{I1}}{m_{I2}-m_{I1}} \\ -\dfrac{1}{m_{I2}-m_{I1}} & \dfrac{1}{m_{I2}-m_{I1}} \end{bmatrix} \begin{bmatrix} C_{I1} \\ C_{I2} \end{bmatrix} \quad (17)$$

where m_{I1} is the gradient of the incident beam to the lower mirror and C_{I1} is the equation constant. The equation constant is given by

$$C_{I1} = y_1 - m_{I1} x_1 \tag{18}$$

where

$$\begin{aligned} x_1 &= r_1 \sin \theta_1 \\ y_1 &= r_1 \cos \theta_1 \end{aligned} \tag{19}$$

are the Cartesian coordinates of the reflection point (r_1, θ_1). The gradient of the incident beam is found using the law of reflection

$$m_{I1} = \tan\left[\tan^{-1}\left(\frac{dy_1}{dx_1}\right) + \tan^{-1}\left(\frac{1}{m_{R1}}\right) - \tan^{-1}\left(\frac{dx_1}{dy_1}\right)\right] \tag{20}$$

where m_{R1} is the gradient of the reflected beam from the lower mirror to the camera and dy_1/dx_1 is the gradient of the lower mirror profile at the reflection point. The gradient of the reflected beam is

$$m_{R1} = \tan \theta_1 \tag{21}$$

The gradient of the mirror profile for the lower variable gain mirror is found as in the constant gain case, from

$$\frac{dy_1}{dx_1} = \frac{dy_1}{d\theta_1} / \frac{dx_1}{d\theta_1}$$
$$= \frac{\frac{dr_1}{d\theta_1}\cos\theta_1 - r_1\sin\theta_1}{\frac{dr_1}{d\theta_1}\sin\theta_1 + r_1\cos\theta_1} \tag{22}$$

where $dr/d\theta$ for either mirror of the variable gain mirror configuration is found by integrating (5) and substituting (12).

$$\begin{aligned} \int d\tan^{-1}\left(r\frac{d\theta}{dr}\right) &= -\frac{1}{2}\int (1 + \alpha(\theta))\, d\theta \\ \tan^{-1}\left(r\frac{d\theta}{dr}\right) &= -\frac{1}{2}\theta - \frac{B_\alpha}{2}\int (\tan(\theta) + \tan^3(\theta))\, d\theta \\ &= -\frac{1}{2}\theta - \frac{B_\alpha}{4}\tan^2(\theta) + D \end{aligned} \tag{23}$$

where D is a constant of integration. Rearranging (23) gives

$$\frac{dr}{d\theta} = r\cot\left(-\frac{1}{2}\theta - \frac{B_\alpha}{4}\tan^2(\theta) + D\right) \tag{24}$$

Now from (23) and (2),

$$D = \gamma + \frac{1}{2}\theta + \frac{B_\alpha}{4}\tan^2(\theta) \tag{25}$$

so, for the lower variable gain mirror profile

$$D_1 = \underline{\gamma_1} + \frac{1}{2}\underline{\theta_1} + \frac{B_\alpha}{4}\tan^2(\underline{\theta_1})$$

similarly for D_2, for the upper variable gain profile.

So, by substituting (24) into (22) gives the gradient of the variable gain mirror profiles at any point. Note that as in the constant gain case, the gradient depends only on θ.

The equation constants for the incident beam equations from (18) require the polar coordinates of the reflection points from each mirror, (r_1, θ_1) and (r_2, θ_2). Since the variable gain mirror equations are not known exactly, r_1 and r_2 must be found using a differential equation solver to find solutions to (26) at θ_1 and θ_2.

2 Back-to-back Stereo Mirror Families

A key disadvantage of single camera stereo panoramic systems is that since there are two images of the "same" scene, the pixels assigned to each image is half that for non stereo panoramic imaging and the two images do not share an equal number of pixels in constant gain schemes. Actually, the panoramic stereo double mirror method typically causes the view of a scene in one radial direction to be compressed into around 1/4 the field of view of the camera.

A method to achieve panoramic stereo with less image compression is to use two cameras and two single curved mirror surfaces back to back, as shown in Fig. 9. This method compresses the imaged scene into 1/2 the field of view of the camera, and indeed each image has an equal share of the total number of pixels available. There are, however, possible alignment problems with this system as with any stereo system using two cameras to capture two views of a scene.

An advantage of the scheme proposed in Fig. 9 is that the stereo cone can be symmetric about

the horizon using two cameras with equal fields of view and the maximum and minimum angles of elevation reflected by the two mirrors being equal. The angle covered by the stereo cone in this case is $2\bar{\phi} - \pi$. Fig.9 shows the general case where the maximum and minimum angles of elevations viewed by each camera need not be equal. The range of elevations must still be equal for the fields of view to be aligned.

The number of free parameters to be specified are reduced here as the minimum angle of elevation ($\underline{\phi}$) and from one mirror must be parallel to the maximum angle of elevation ($\bar{\phi}$) from the other mirror. This is to ensure that the fields of view are parallel. So, with reference to Fig. 9

$$\underline{\phi} = \pi - \bar{\phi} \tag{26}$$

In the scheme of Fig. 9, the mirror families can be either constant gain or resolution invariant.

2.1 The Use of Double Mirrors in a Back to Back Design

Fig. 10 shows a back to back design incorporating double mirrors. Although the figure shows constant gain mirrors, the double mirror can also have a variable gain. The advantage to this system is that the stereo cone from the back to back configuration combines with the stereo cones from the double mirror configuration to increase the total area imaged in stereo. In this configuration, the fields of view of each double mirror pair need not be aligned as in previous examples. For symmetry about the horizon $\underline{\phi}_3 = \underline{\phi}_1$, $\underline{\phi}_4 = \underline{\phi}_2$, $\bar{\phi}_3 = \bar{\phi}_1$ and $\bar{\phi}_4 = \bar{\phi}_2$. The constraints

$$\overline{\phi_3} = \pi - \overline{\phi_2}$$
$$\overline{\phi_4} = \pi - \overline{\phi_1}$$

align the three stereo cones.

It is also possible to increase the total stereo cone further by allowing the mirror pairs to have different gains.

3 Forward Looking Mirror Design

An example of a forward looking mirror design is shown in Fig. 11. For many applications, it is desirable to have a panoramic camera looking out from, say, a hemisphere, somewhat as an eye of a bird, or perhaps two such on either side of a "nose cone". There are aerodynamic considerations or other protrusion considerations which motivate such a "forward looking" system. This configuration is termed forward looking because the camera faces towards the scene. Either a constant or variable gain mirror (double or single) could be used for the curved mirror in the system. The planar mirror is an annulus or circle interposed such that all rays reflected from the curved mirror are reflected into camera o positioned behind the curved mirror. The dotted lines in Fig. 11 show where the reflected rays would converge if the planar mirror was removed and the dotted camera shows the camera o' for an equivalent system without the planar mirror.

In order for the rays reflected by the planar mirror to converge at the new camera position, the planar mirror must be the perpendicular bisector of the line joining the old and new camera locations. Hence the distance between the camera locations is $2D$ where D is defined in Fig. 11 as the distance from either camera to the planar mirror. The introduction of the planar mirror into the system does increase the possibility of alignment difficulties as the planar mirror must be perpendicular to the camera axis and also be positioned so as to reflect all rays from the curved mirror into the camera without occluding the view of the curved mirror.

The maximum value for $D,\overline{D}$, is when the maximum beam reflected from the mirror system (the $\overline{\theta}$ beam reflected at point *b* on the planar mirror) into camera *o* grazes the curved profile at *c*. In this case

$$\overline{D} = \frac{\underline{r}\cos(\underline{\theta})[\tan(\underline{\theta}) + \tan(\overline{\theta})]}{2\tan(\overline{\theta})} \quad \textbf{(27)}$$

$\overline{D}$, defines the minimum height for the mirror system, $\underline{H}$. In practice, the value for D needs to be slightly smaller to avoid occlusion, leading to a larger mirror system height. The general equation for the height of the mirror system is

$$H = \bar{r}\cos(\overline{\theta}) - D \quad \textbf{(28)}$$

It should also be noted that $\underline{\theta}$ must be greater than zero for camera *o* to be located behind the curved mirror. Also, $\underline{\phi} \geq \overline{\theta}$ if the minimum elevation ray $\underline{\phi}$ is not to be occluded by the planar mirror.

Fig. 12 shows a design that incorporates the ideas of Sections 2 and 3. It consists of two forward looking systems back to back, giving a design reminiscent of a eye mounted on a stalk, such as a crab's eye. The "stalk" for this system would be hidden from view by the lower planar mirror. In this arrangement portions are provided in the curved mirror to provide for reflection of rays from the curved surface to the camera by the plane mirrors.

The foregoing describes only some aspects of the present invention and modifications can be made without departing from the scope of the invention.

CLAIMS:

1. A panoramic imaging system including an imaging device having an image plane and a first field of view, a first reflective surface having at least one circularly symmetric portion convex in a radial direction disposed in said first field of view to provide an expanded panoramic second field of view, the profile of the or each convex portion providing a varying gain between the fields of view in the radial direction to limit variation in the solid angle of view across the image plane of the imaging device.

2. A panoramic imaging system as claimed in claim 1 wherein the profile of the or each convex portion provides a substantially uniform solid angle of view across the image plane.

3. A panoramic imaging system as claimed in claim 1 or claim 2 wherein the profile of the or each convex portion at least approximates a profile defined in polar co-ordinates by the equation:

$$\frac{dr}{d\theta} = r \cot\left[-\tfrac{1}{2}\int(1 + \alpha(\theta))\,d\theta\right]$$

where r is the radial distance from the reflective surface to the imaging device
θ is the angle from the optical axis of the imaging device
$\alpha(\theta)$ is the mirror gain given by

$$\alpha(\theta) = B_\alpha\,[\tan(\theta) + \tan^3(\theta)]$$

$$B_\alpha = \frac{2(\overline{\phi} - \underline{\phi})}{\tan^2(\overline{\theta}) - \tan^2(\underline{\theta})}$$

$\overline{\phi}$ and $\underline{\phi}$ are the maximum and minimum elevations viewed $\overline{\theta}$ and $\underline{\theta}$ are the maximum and minimum radial angles imaged.

4. A panoramic imaging system as claimed in claim 3 wherein the profile of the or each convex portion includes by a series spaced apart points defined by determining distance *r* for selected values of angle θ.

5. A panoramic imaging system as claimed in claim 4 wherein the selected values of θ are separated by about 1/5°.

6. A panoramic imaging system as claimed in any one of claims 1 to 5 including a first reflector surface having at least two of said convex portions arranged to respectively provide at least partially overlapping panoramic second fields of view for range determination.

7. A panoramic imaging system as claimed in claim 6 wherein said panoramic second fields of view are substantially co-incident.

8. A panoramic imaging system as claimed in claim 7 wherein said at least two convex portions form a continuous reflective surface.

9. A panoramic imaging system as claimed in any one of claims 1 to 8 including two of said first reflective surfaces each having an associated image plane with corresponding first fields of view, and at least one convex portion of each first reflective surface providing respective panoramic second fields of view, said first reflective surface being arranged back to back such that said reflective second fields of view at least partially overlap.

10. A panoramic imaging system as claimed in any one of claims 1 to 9 further including a second reflective surface interposed between the image plane and said second reflective surface.

11. A panoramic imaging system as claimed in claim 10 wherein the imaging device is positioned behind the second reflective surface.

12. A panoramic imaging system as claimed in claim 11 wherein an aperture is provided in said first reflective surface to provide said first field of view from the imaging device.

13. A panoramic imaging system as claimed in any of claims 10 to 12 wherein said second reflective surface is substantially planar.

14. A reflective surface for use in a panoramic imaging system including an imaging device having an imaging plane and a first field of view, said reflective surface having at least one circularly symmetric portion convex in a radial direction with a profile providing varying gain in the radial direction between an expanded panoramic second field of view provided by the reflective surface and the first field of view to limit variation in the solid angle of view across the image plane of the imaging device.

15. A reflective surface as claimed in claim 14 wherein the profile of the or each convex portion provides a substantially uniform solid angle of view across the image plane.

16. A reflective surface as claimed in claim 14 or claim 18 wherein the profile of the or each convex portion at least approximates a profile defined in polar co-ordinates by the equation:

$$\frac{dr}{d\theta} = r \cot \left[- \tfrac{1}{2} \int (1 + \alpha(\theta))\, d\theta \right]$$

where r is the radial distance from the reflective surface to the imaging device

θ is the angle from the optical axis of the imaging device

$\alpha(\theta)$ is the mirror gain given by

$$\alpha(\theta) = B_\alpha [\tan(\theta) + \tan^3(\theta)]$$

$$B_\alpha = \frac{2(\overline{\phi} - \underline{\phi})}{\tan^2(\overline{\theta}) - \tan^2(\underline{\theta})}$$

$\bar{\phi}$ and $\underline{\phi}$ are the maximum and minimum elevations viewed $\bar{\theta}$ and $\underline{\theta}$ are the maximum and minimum radial angles imaged.

17. A reflective surface as claimed in claim 16 wherein the profile of the or each convex portion includes by a series spaced apart points defined by determining distance *r* for selected values of angle θ.

18. A reflective surface as claimed in claim 17 wherein the selected values of θ are separated by about 1/5°.

19. A reflective surface as claimed in any one of claims 14 to 18 including a first reflector surface. having at least two of said convex portions arranged to respectively provide at least partially overlapping panoramic second fields of view for range determination.

20. A reflective surface as claimed in claim 19 wherein said panoramic second fields of view are substantially co-incident.

21. A reflective surface as claimed in claim 20 wherein said at least two convex portions form a continuous reflective surface.

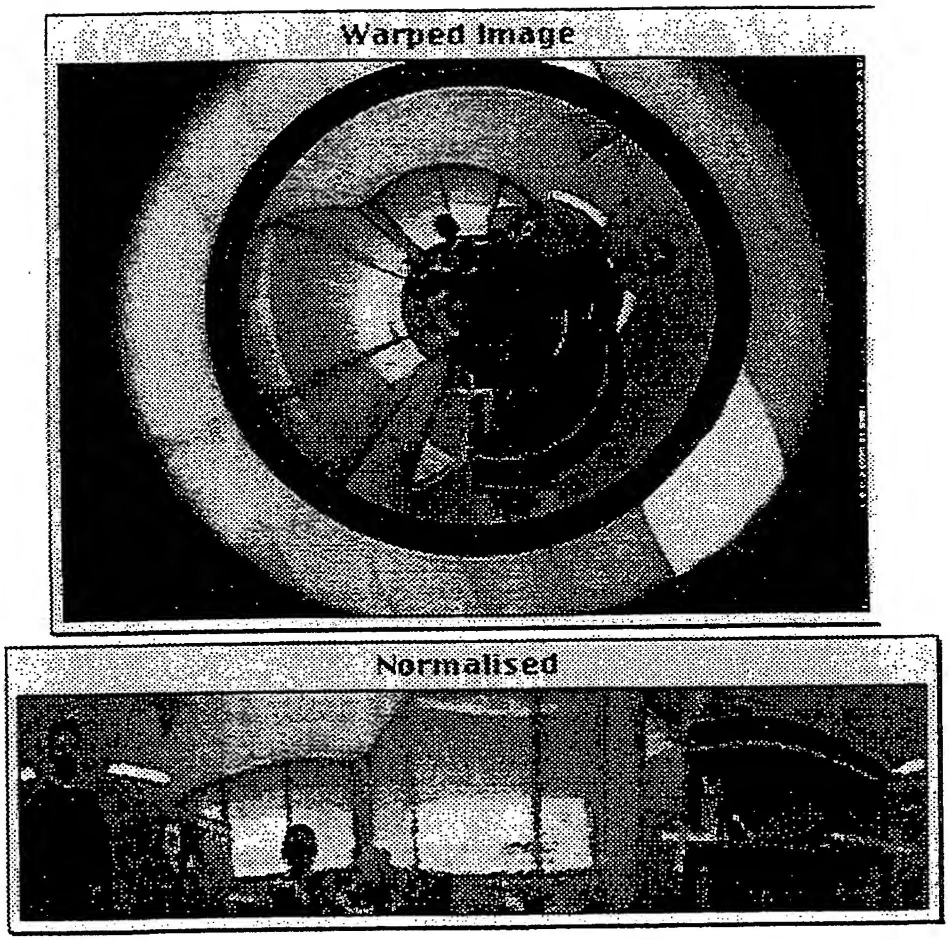


FIGURE 1

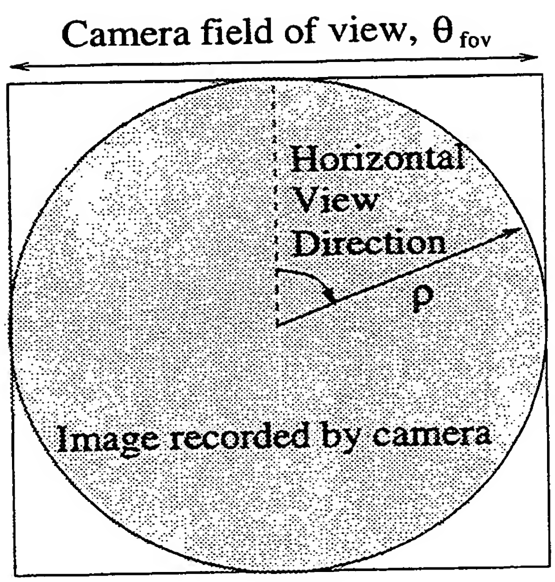

Camera field of view, θ fov
Horizontal
View
Direction
ρ
Image recorded by camera

FIGURE 2

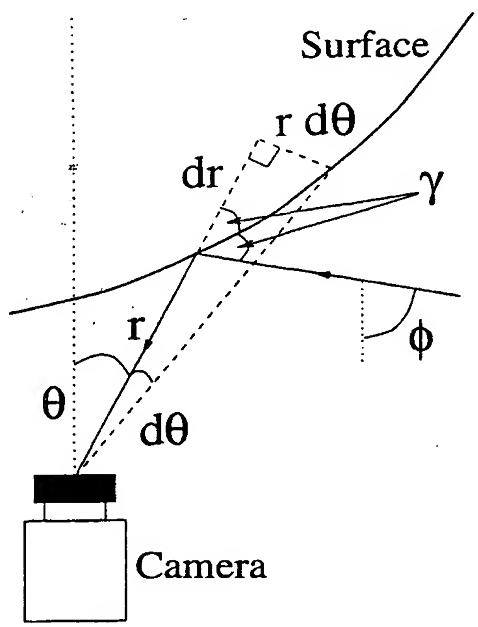


FIGURE 3

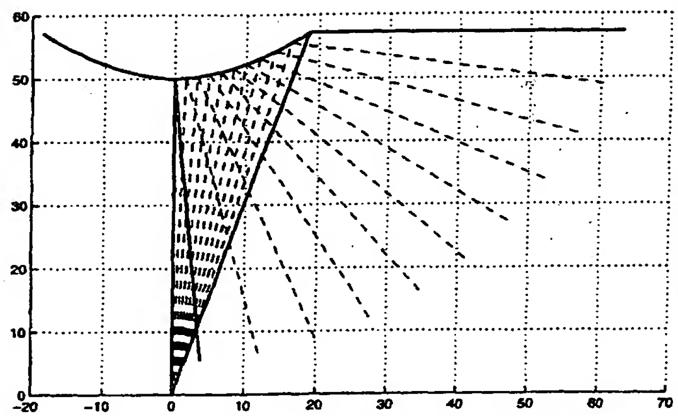


FIGURE 4A

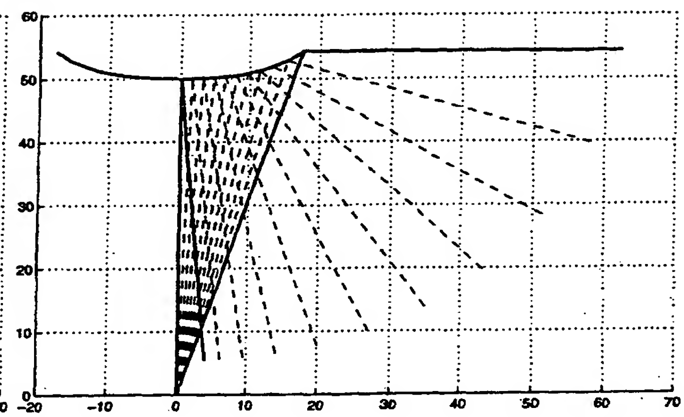


FIGURE 4B

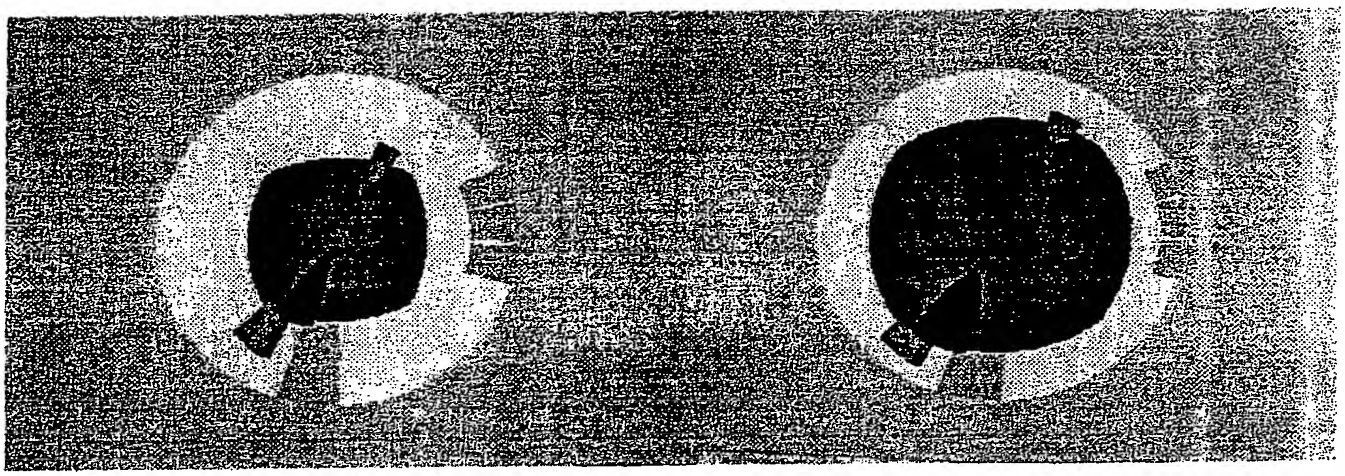


FIGURE 5A FIGURE 5B

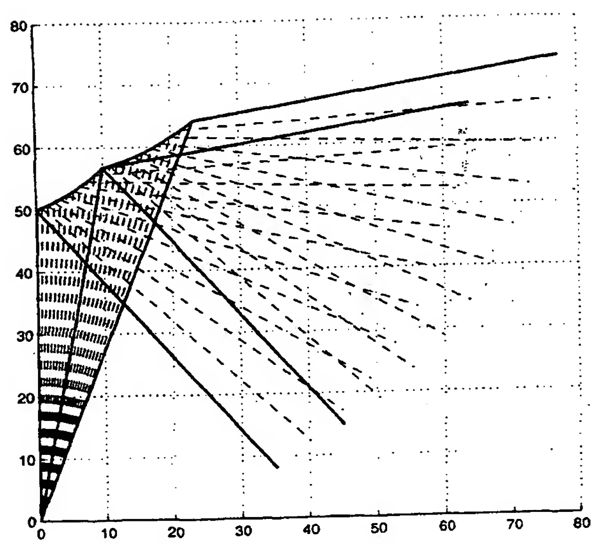


FIGURE 6A

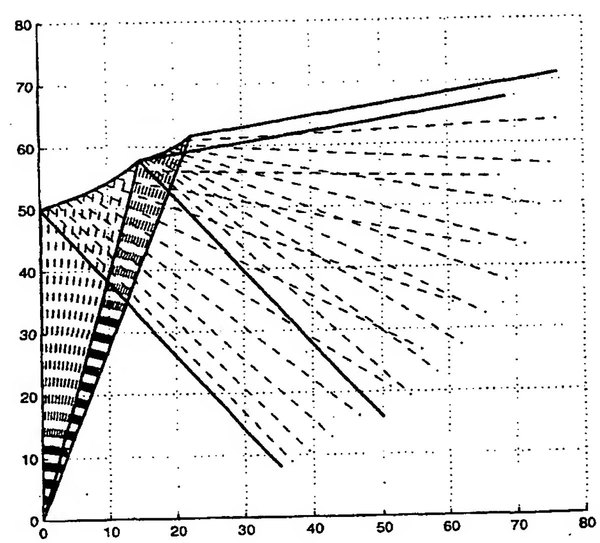


FIGURE 6B

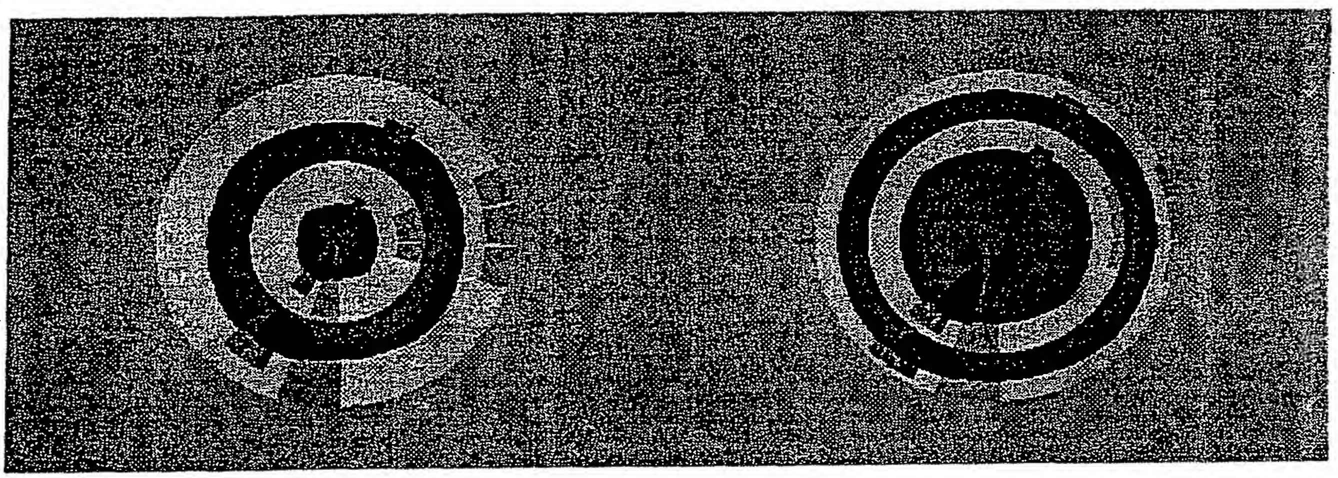


FIGURE 7A FIGURE 7B

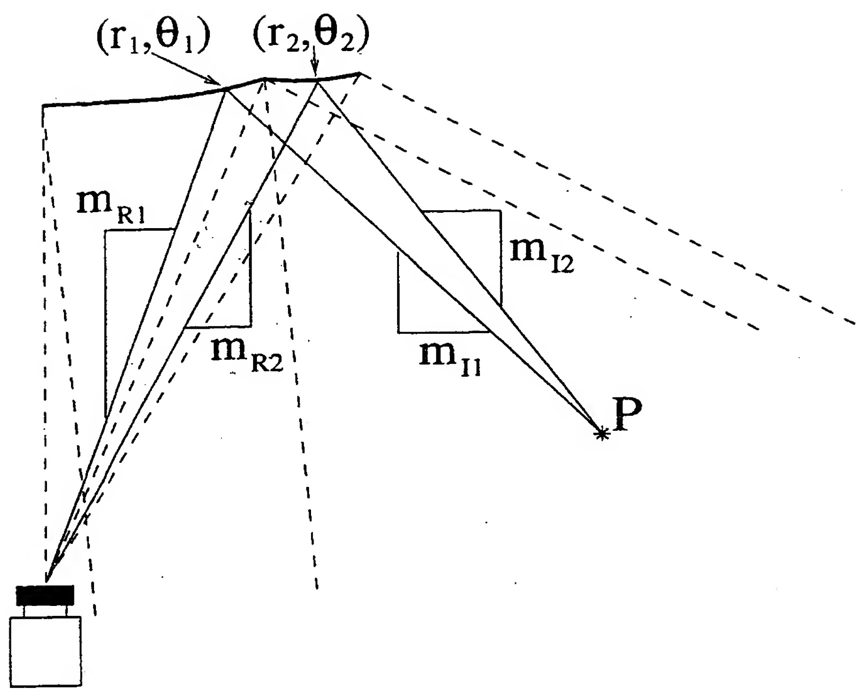


FIGURE 8

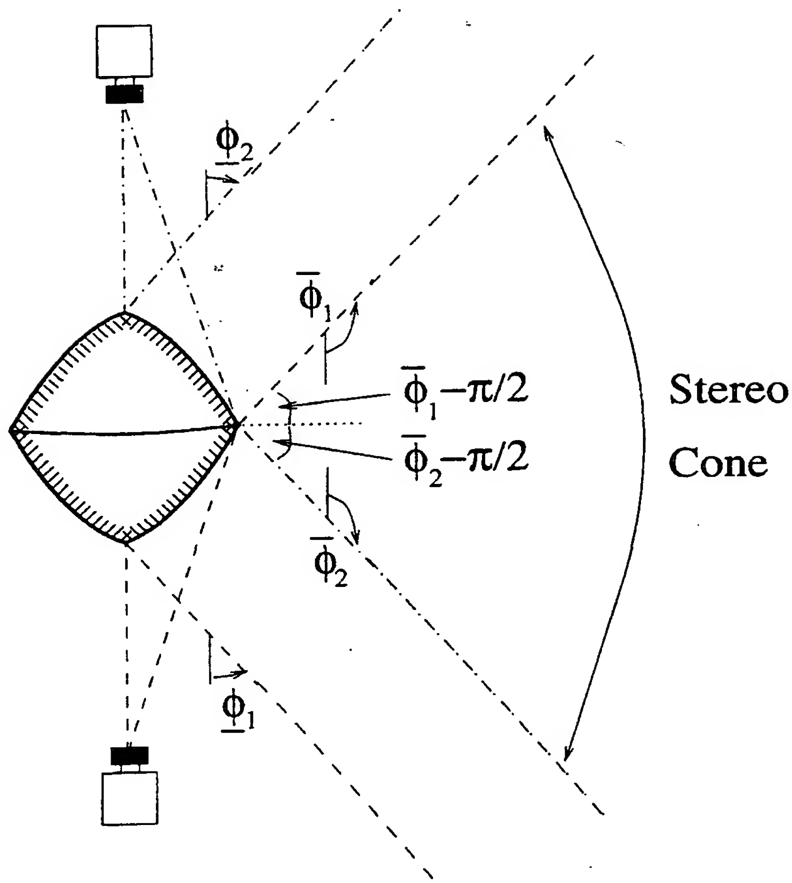

$\underline{\phi}_2$
$\bar{\phi}_1$
$\bar{\phi}_1-\pi/2$
$\bar{\phi}_2-\pi/2$
$\bar{\phi}_2$
$\underline{\phi}_1$
Stereo
Cone

FIGURE 9

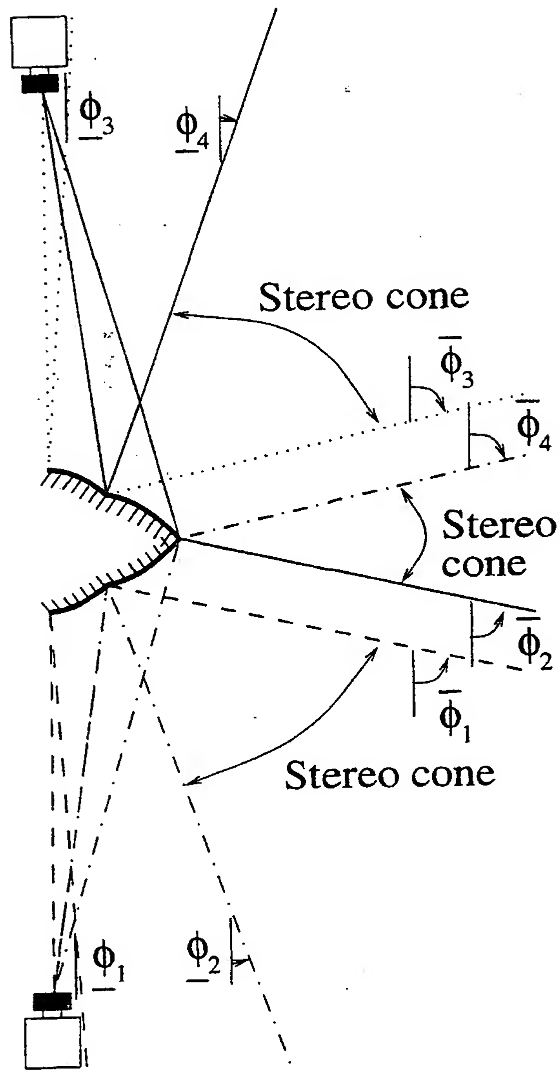

$\underline{\phi}_3$
$\underline{\phi}_4$
Stereo cone
$\overline{\phi}_3$
$\overline{\phi}_4$
Stereo cone
$\overline{\phi}_2$
$\overline{\phi}_1$
Stereo cone
$\underline{\phi}_1$
$\underline{\phi}_2$

FIGURE 10

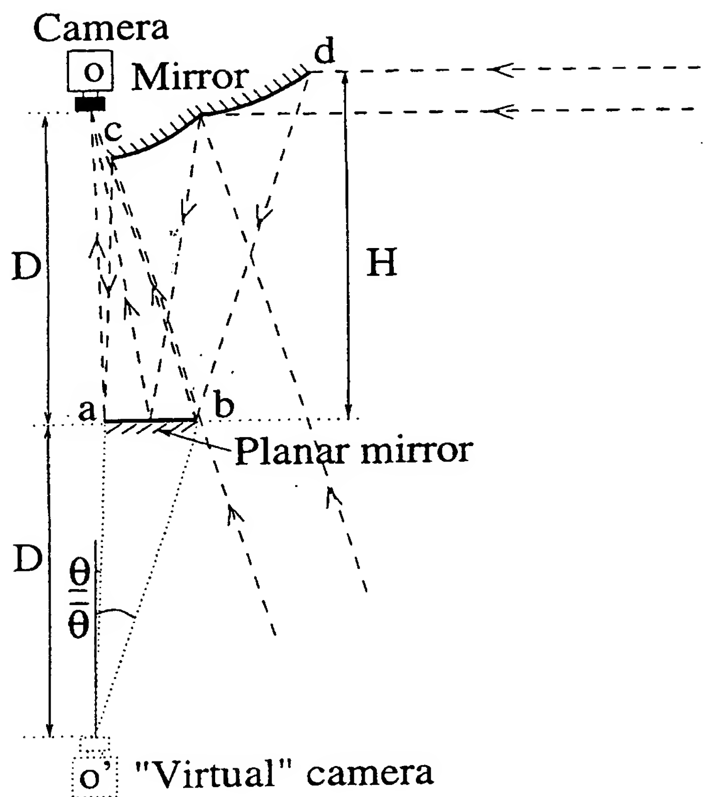


FIGURE 11

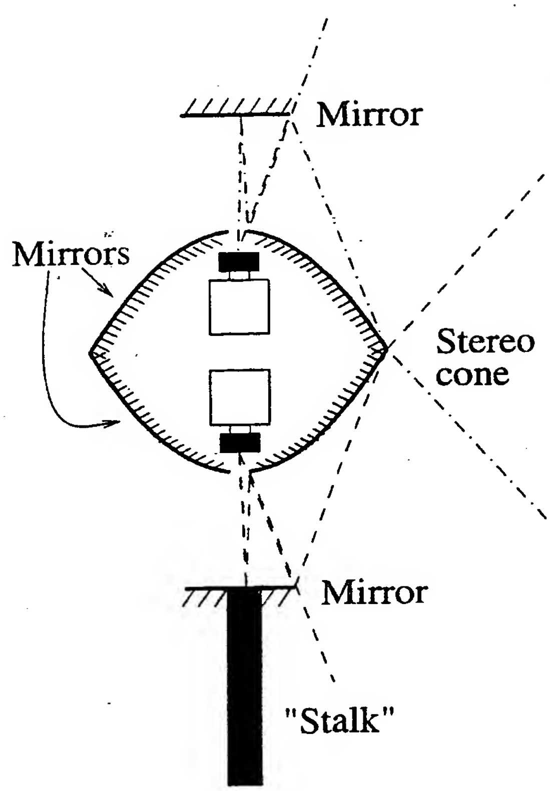


FIGURE 12

INTERNATIONAL SEARCH REPORT

International application No.
PCT/AU 00/00022

A. CLASSIFICATION OF SUBJECT MATTER

Int Cl^{7}: G03B 37/00, G02B 5/10, 13/06, 17/06, B25J 19/04

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC: G03B 37/00, G02B 5/10, 13/06, 17/06, 23/08, B25J 19/04

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
AU: IPC AS ABOVE

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
DWPI, JAPIO

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	AU 74861/94 (673951) B (THE AUSTRALIAN NATIONAL UNIVERSITY) 21 March 1995 page 6 line 4 - page 14 line 14	1-5, 14-18
X	US 4566763 A (GREGUSS) 28 January 1986 Col 1 line 66 - col 2 line 16, fig 4	1, 14
A	US 5627675 A (DAVIS et al) 6 May 1997 Whole document	

[X] Further documents are listed in the continuation of Box C

[X] See patent family annex

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search
17 February 2000

Date of mailing of the international search report
21 FEB 2000

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INTERNATIONAL SEARCH REPORT

International application No.
PCT/AU 00/00022

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5502309 A (DAVIS) 26 March 1996 Fig 5	
A	US 4549208 A (KAMEJIMA et al) 22 October 1985 Col 3	
A	US 4449786 A (McCORD) 22 May 1984 Col 5 line 38 - col 7 line 24, Figs 5, 8, 13	

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/AU 00/00022

This Annex lists the known "A" publication level patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent Document Cited in Search Report		Patent Family Member					
AU	74861/94	WO	9506303	EP	715743	US	5790181
US	4566763	DE	3402847	FR	2540642	JP	59192220
US	5627675	EP	833178				

END OF ANNEX

Form PCT/ISA/210 (citation family annex) (July 1998)